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An Invitation to Geology

Within the solar system, earth's abundant surface water imparts a unique ability to support life as we know it, and air and water together continually reshape earth's surface.
© NASA.

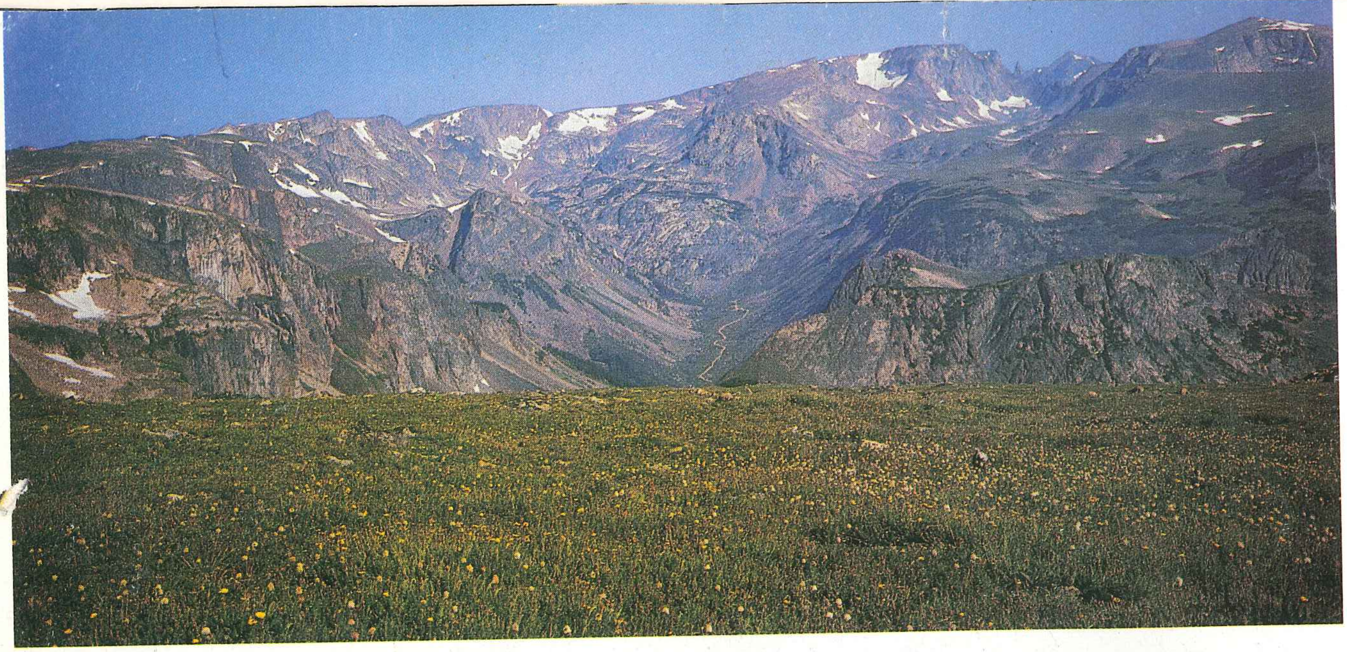

FIGURE 1.1 Careful application of geologic principles may allow the history of a mountain range to be deciphered. The Beartooth Mountains near Yellowstone National Park.

Introduction

Geology is the study of the earth and the processes that shape it. **Physical geology,** in particular, is concerned with the materials and physical features of the earth, changes in those features, and the processes that bring them about. Intellectual curiosity about the way the earth works is one reason for the study of geology. Piecing together the history of a mountain range (figure 1.1) or even a single rock can be exciting. The nonspecialist can better appreciate the physical environment—from distinctive features like the granite domes of Yosemite or the geysers of Yellowstone (figure 1.2) to the rocks exposed in a roadcut or found in one's own back yard.

There are also practical aspects to the study of geology. Certain geologic processes and events can be hazardous (figure 1.3), and a better understanding of such phenomena may help us to minimize the risks. We have also come to depend heavily on certain earth materials for energy or as raw materials for manufacturing (figure 1.4), and knowing how and where those resources can be found can be very useful to modern society.

Before entering into the detailed study of physical geology, we briefly survey geology as a discipline and some basic characteristics of the earth that is its subject.

Geology As a Discipline

Geology is a particularly broad-based discipline, for it draws on many other sciences. Knowledge of physics contributes to an understanding of rock structures and deformation, and supplies tools with which to investigate the earth's deep interior indirectly. The chemistry of geologic materials—rocks, minerals, fossils, fuels—provides clues to their origins and history. Modern biological principles are important in studying ancient life forms. Mathematics provides a quantitative framework within which geologic processes can be described and analyzed. Physical geographers study the earth's surface features much as some geologists do. What makes geology a distinctive discipline is, in part, that it focuses all these approaches, and others, on the study of the earth. Moreover, having the earth as a subject also introduces some special complexities not common to most other sciences.

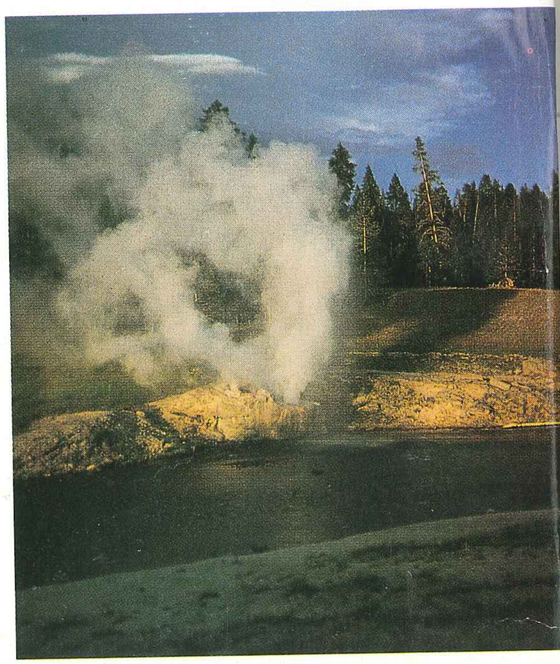

FIGURE 1.2 Eruption of Riverside Geyser, Yellowstone National Park.

The Special Problems of Time and Scale

The modern earth has been billions of years in the making. As will be seen in later chapters, many of the processes shaping the earth are extremely slow on a human time scale, some barely detectable even with

FIGURE 1.3 **Fourth Avenue landslide, Anchorage, Alaska, after the 1964 earthquake. Note how far the shops and street on the right have dropped relative to the left side of the street.**
Photograph courtesy of USGS Photo Library, Denver, CO.

FIGURE 1.4 **The world's largest open-pit mine. Bingham Canyon, Utah. Over $6 billion worth of minerals has been extracted from this one mine over the decades of its operation.**
Photograph courtesy of Kennecott.

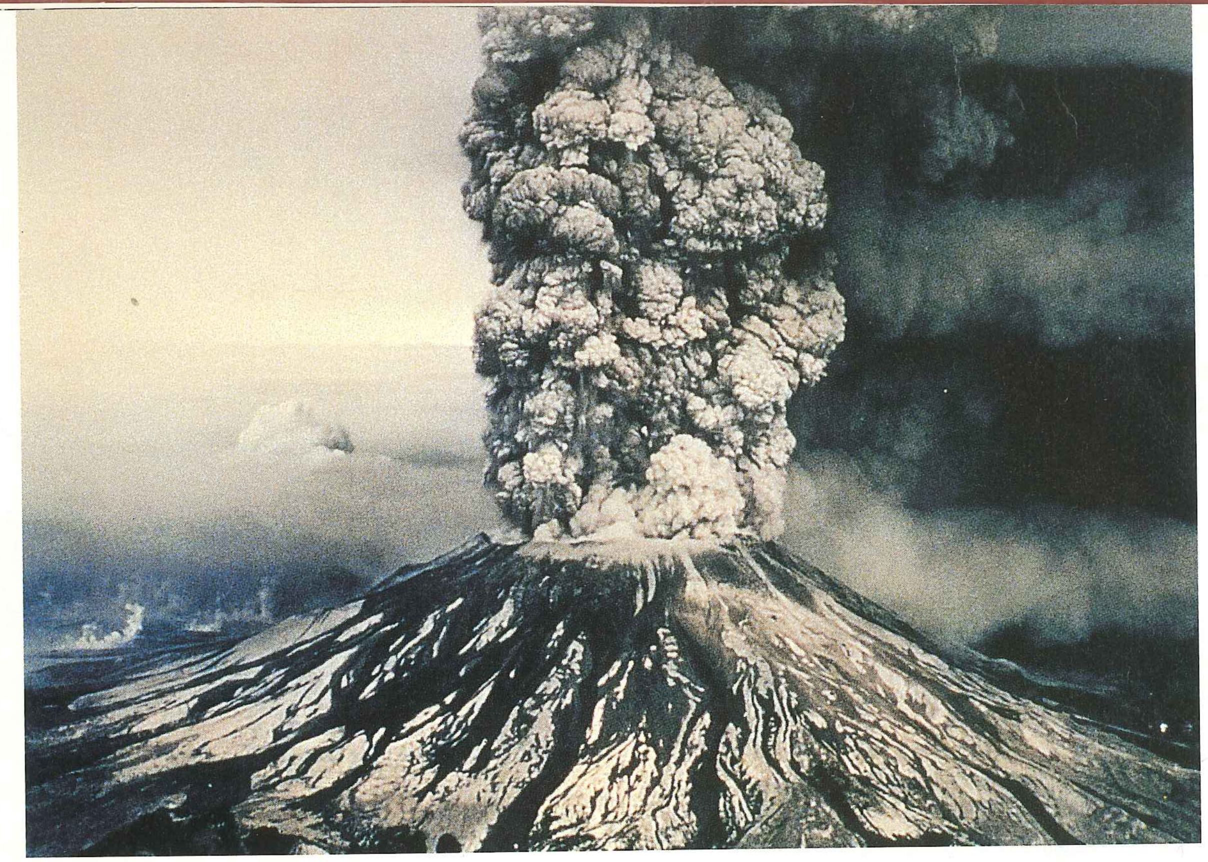

FIGURE 1.5 **Mount St. Helens in eruption, May 1980.**
Photograph by P. W. Lipman, USGS Photo Library, Denver, CO.

sensitive instruments. It is therefore difficult to observe or to demonstrate directly, in detail, how certain materials or features have formed.

Furthermore, a given material may respond differently to the same forces, depending on how those forces are applied. This can be seen, for example, in the phenomenon of fatigue of machine parts, in which a material quite strong enough to withstand a certain level of sustained stress fails during the application of a much smaller stress that has been repeated many times. As a practical matter, then, it may be impossible to duplicate some geologic processes in the laboratory because the human lifetime is simply too short.

Likewise, some natural systems are just too large to duplicate in the laboratory. A single crystal or small piece of volcanic rock can be studied in great detail. But it is hardly possible to build a volcano (figure 1.5), or a whole continent, in a laboratory to conduct experiments on them. Scale-model experiments, in which the materials and the forces applied to them are scaled down proportionately, are one compromise. For example, in studies of designs for earthquake-resistant buildings, model structures are shaken by small vibrations in the hope that the results will mimic the response of large buildings to great earthquakes. As another example, a large tank of water can be agitated artificially to study wave motion or the effects of currents. Scale modeling is an inexact science, however, and not all natural systems lend themselves to such studies. The alternative, for the study of large features, may be extensive travel and field work, and perhaps even use of a satellite's broad perspective from space.

Complexity in Natural Systems

A laboratory scientist about to conduct an experiment tries to minimize the number of variables, so as to obtain as clear a picture as possible of the effect of any one change—whether of temperature, pressure, or the quantity of some particular substance present. Typically, the experimental materials are kept simple: a single rock type or mineral, chemically quite pure. Natural geologic systems, however, are rarely so simple. Natural rocks and minerals invariably contain chemical impurities and physical imperfections; many different rocks and minerals may be mixed together; and temperature and pressure may change simultaneously, while gases, water, or other chemicals flow in and out. Extrapolating from carefully controlled laboratory experiments to the real world becomes correspondingly difficult.

Also, the laboratory scientist can perform an experiment in stages, examining the results after each step. The geologist, however, may be confronted by rocks or other materials or structures that have been altered or recycled several times, perhaps dozens of times, each time under different conditions, over millions or even billions of years. That history

can be difficult to decipher from the present end product, particularly because the same end product can often be formed from several different possible starting materials, via different combinations of geologic processes, just as one can arrive at a given spot by traveling in various ways from various starting points.

Geology and the Scientific Method

The **scientific method** is a means of discovering basic scientific principles. One begins with a set of observations and/or a body of data that are based on measurements of natural phenomena or on experiments. One or more **hypotheses** are formulated to explain the observations or data. It is also possible that no systematic relationship exists among the observations *(null hypothesis)*. A hypothesis can take many forms, ranging from a general conceptual framework or physical model describing the functioning of a natural system, to a very precise mathematical formula relating several kinds of numerical data. What all hypotheses have in common is that they are unproven and must be susceptible to testing.

In the classical conception of the scientific method, one uses a hypothesis to make a set of predictions and then devises and conducts experiments to test each hypothesis to determine whether experimental results agree with predictions based on the hypothesis. If they do, the hypothesis gains credibility. If not, if the results are unexpected, the hypothesis must be modified to account for the new data. Several cycles of modifying and retesting hypotheses may be required before a hypothesis that is consistent with all the observations and experiments that one can conceive is developed. A hypothesis that is repeatedly supported by new experiments advances, in time, to the status of a **theory,** a generally accepted explanation for a set of data or observations.

In addition to hypotheses and theories, there is a smaller body of scientific **laws:** fundamental, typically simple principles or formulas that are invariably found to be true. In this category are Newton's law of gravity and the principle of physical chemistry that states that heat always flows from a warmer body to a colder one, never the reverse.

The approach outlined in the foregoing description of the scientific method is not strictly applicable to many geologic phenomena because of the difficulty of experimenting with natural systems. In such cases, hypotheses are often tested entirely through further observations and modified as necessary until they accommodate all the relevant observations. This broader conception of the scientific method is well illustrated by the development of the theory of plate tectonics, discussed in chapter 9. Even a well-accepted theory, however, may ultimately be found to require extensive modification. In the case of geology, a common cause of this is the development of new analytical or observational techniques, which make available wholly new kinds of data that were unknown at the time the original theory was formulated.

Key Concepts in the History of Geology

Humans have wondered about the earth in some way for thousands of years. The ancient Greeks measured it and recognized fossils preserved in its rocks as remains of ancient life forms. Theologians, philosophers, and scientists have speculated on its age for centuries. The systematic study of the earth that constitutes the science of geology, however, has existed as an organized discipline for only about 250 years. It was first developed formally in Europe. In its early years, it was predominantly a descriptive subject. Two principal opposing schools of thought emerged in the eighteenth and nineteenth centuries to explain geologic observations.

One, popularized by James Hutton and later named by Charles Lyell, was the concept of **uniformitarianism.** Sometimes condensed to the phrase, "The present is the key to the past," uniformitarianism comprises the ideas that the surface of the earth has been continuously and gradually changed and modified over the immense span of geologic time and that, by studying the geologic processes now active in shaping the earth, we can understand how it has evolved through time. It is not assumed that the *rates* of all processes have been the same throughout time, but rather that the nature of the processes is similar—that the same physical principles operating on the earth in the past also are operating in the present.

> Scotsman James Hutton was a remarkably versatile individual—physician, farmer, and only part-time geologist. In the early days of the science, many advances in understanding were made by nonspecialists capable of careful observation and logical deduction. As various disciplines become more advanced and more sophisticated, however, the amateur is far less able to play a major role. Too much accumulated knowledge must be assimilated to arrive at the forefront of research.

The second, contrasting theory was **catastrophism.** The catastrophists, led by French scientist Georges Cuvier, believed that a series of immense, worldwide upheavals were the agents of change and that, between catastrophes, the earth was static. Violent volcanic eruptions followed by torrential rains and floods were invoked to explain mountains and valleys and to bury animal populations that later became fossilized. In between those episodic global devastations, the earth's surface did not change, according to catastrophist theory. Catastrophists also believed that entire plant and animal populations were created anew after each such event, to be wholly destroyed by the next.

FIGURE 1.6 **Meteor Crater, Arizona.**

Is the Present the Key to the Past?

More detailed observations and calculations, greater use of the allied sciences, and development of increasingly sophisticated instruments have collectively provided overwhelming evidence in support of the uniformitarian view. The great length of the earth's history makes it entirely plausible that processes that seem gradual and even insignificant on a human time scale could, over those long spans of time, create the modern earth in all its geologic complexity.

This is not to say that earth history has not been punctuated occasionally by sudden, violent events that have had a substantial impact on a regional or global scale. Geologists see evidence of past collisions of large meteorites with the earth (figure 1.6) and find volcanic debris from ancient eruptions that would dwarf that of Mount St. Helens. But these events are unusual and, for the most part, of only temporary significance in the context of the earth's long history. By and large, the modern earth is the product of uncounted small and gradual changes, repeated or continued over very long spans of time.

> Evolution of organisms provides a biological analogy. Such evolution is, for the most part, a process of many small, individual, adaptive changes that collectively amount, over time, to a significant change in the basic characteristics of the species. Occasionally, however, there are much more rapid changes, caused perhaps by unusual mutations or extraordinary environmental stresses, and sometimes, whole plant or animal groups rapidly decline and become extinct.

The same physical and chemical laws can be presumed to have operated throughout earth's history. Thus, by observing modern geologic processes, geologists can learn much about how those same processes might have shaped the earth in the past. The relative importance of each process, however, may not always have been just the same as it is now; nor can it be assumed that all processes operated in detail just as they do now. Certain irreversible changes in the earth have no doubt changed the nature and intensity of corresponding geologic processes. For example, the earth has been slowly losing heat since it formed. Present internal temperatures must be substantially lower than they were several billion years ago, especially near the surface. The earth's internal heat plays a key role in melting rocks and thus in volcanic activity, as well as in plate tectonics (see box 1.1). It is reasonable to infer that melting in the interior was more extensive in the past than it now is, that the products of that more extensive melting might be somewhat different from modern volcanic rocks, and also that volcanic activity was more extensive in the past. The earth's atmosphere, too, has undergone profound changes, as is explored further shortly. Briefly, the atmosphere has gone from oxygen-poor to oxygen-rich, and this change, in turn, has necessarily affected the chemical details of such processes as weathering of rocks by interaction with air and water. However, geologists can determine, experimentally and theoretically, how rocks would react with the kind of atmosphere deduced for the early earth and thus characterize ancient weathering processes, even though they cannot observe the exact equivalents in nature today. The *earth* may change; the *physical laws* do not. This concept is fundamental to modern uniformitarianism.